

Implementation of Cylindrical Dielectric Resonator Antenna Array for Wi-Fi/Wireless LAN/Satellite Applications

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Abstract—A tri-band Cylindrical Dielectric Resonator Antenna (CDRA) array is proposed for WiFi, wireless LAN, and satellite applications in this paper. CDRA is massively demanded by various smart wireless devices. The claimed antenna array structure is developed and fabricated using an FR4 substrate having relative permittivity (ϵ_r) of 4.4. Microstrip power divider line is utilised for array excitation. The variation in return loss due to the effect of varying microstrip line length, dielectric resonator height, and ground plane height has been carefully recorded and presented using parametric study. The array structure is engineered for triple-band operations working at 2.4 GHz, 4.1 GHz, and 5.4 GHz frequencies. To achieve adequate bandwidth accompanied by acceptable gain is a very inspiring task. The proposed structure shows a promising maximum impedance bandwidth of 1.14 GHz (40%) and a maximum gain of 9 dBi. The return loss and radiation pattern computed through CST software are verified by practical measurements using VNA device and anechoic chamber atmosphere.

1. INTRODUCTION

In the era of smart devices, mobile and satellite communication systems need an intelligent structure having properties like wideband, moderate gain, reduced size, and multiband operation. The phenomenal growth in wireless communication has directed to wideband and multiband antenna development which satisfy higher bandwidth for satellite and wireless data users. The research shows that printed antenna could be used for millimeter wave applications. Similarly, microstrip antenna is a preferred antenna in many communication applications because of its simplicity and low profile operations, but output parameters like narrow bandwidth, reduction in gain, and efficiency suffer significantly due to metallic and surface wave loss [1–3]. In comparison with microstrip antenna, the DRA gives much wider bandwidth because the entire structure of DRA radiates except ground plane where in microstrip antenna only thin slots radiate. Approximately 10% of bandwidth could be achieved using about 10 of relative permittivity. In addition, DRA has the ability to avoid surface waves which is another attractive feature in comparison with a microstrip antenna. Dielectric resonator antenna attracts researcher's concentration due to its attractive structure which does not suffer from metallic losses due to the absence of metal which results in wide bandwidth, increased gain, and high efficiency [4, 5]. DRA structures of multiple shapes are available in the market like hemispherical, triangular, cylindrical, rectangular, etc. ones [6]. Cylinder-shaped DRAs are easy to engineer compared with rectangular and hemispherical DRAs. To achieve desired operating frequency and bandwidth, the aspect ratio should be carefully maintained. Several feeding mechanisms are used for coupling energy to DRA such as aperture, coaxial probe, conformal patch, and microstrip [7]. The coaxial probe and aperture-coupled feeding methods are widely used in comparison with microstrip. For large antenna array design, direct microstrip feeding method is the most appropriate method [8]. Research shows that using two segments, 8 element DRA array antenna design, 17% bandwidth with 13.8 dB gain had been

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achieved between 5.05 GHz and 5.9 GHz frequency band [9]. Similarly, cylindrical dielectric resonator (Alumina Ceramic) design achieved 27% bandwidth with 7.95 dB gain between 3.5 GHz and 4.75 GHz frequency band [10]. Literature survey shows that linear four element CDRA (Rogers 3010) has been analysed that gave 500 MHz impedance bandwidth at 7.5 GHz with the gain of 10 dBi in [11]. Rana and Parui presented a paper where a wideband CP antenna using a rectangular dielectric resonator (Eccostock HIK) was designed which responded quite well [12]. Utilising various feeding techniques for different shape DRA structures, adequate bandwidth with reasonable gain could be achieved [13–17]. In DRA analysis, one assumption is made that all DRA surfaces are perfect magnetic conductors ignoring the feed probe. For such a kind of cavity, wave functions are transverse magnetic to z and transverse electric to z . The aforesaid wave functions are written as in following Equations (1) and (2) [4]:

$$\psi TE_{npm} = J_n\left(\frac{x_{np}}{a}\rho\right) \left\{ \begin{array}{l} \sin n\theta \\ \cos n\theta \end{array} \right\} \sin \left[\frac{(2m+1)\pi z}{2d} \right] \quad (1)$$

$$\psi TM_{npm} = J_n\left(\frac{x'_{np}}{a}\rho\right) \left\{ \begin{array}{l} \sin n\theta \\ \cos n\theta \end{array} \right\} \cos \left[\frac{(2m+1)\pi z}{2d} \right] \quad (2)$$

The resonance frequency of npm mode can be found by the following Equation (3) [4].

$$f_{npm} = \frac{1}{2\pi a \sqrt{\mu\epsilon}} \sqrt{X_{np}^2 + \left[\frac{\pi a}{2d} (2m+1) \right]^2} \quad (3)$$

In this paper, the tri-band dielectric resonator antenna array is briefly discussed where CDRA is excited by microstrip line feed. In this developed antenna array structure, a four-way power divider is introduced to justify design requirements such as power division, sufficient suppression, and proper phase distribution. The proposed antenna has been fabricated using an FR4 substrate and Alumina Ceramic based CDRA. The designed antenna array obtains an impedance bandwidth of 1.14 GHz (40%) and a maximum gain of 9 dBi with tri-frequency band. The presented research paper is divided into the following sections for better understanding: i) designing of a single element and double elements array ii) designing of developed four elements array iii) parametric study of the proposed antenna iv) result and discussion and v) conclusion.

2. ANTENNA DESIGN

Theoretically, the gain of antenna structure increases with the number of elements in an array. Gain is closely associated with the directivity of the antenna where efficiency of an antenna is also taken into calculations. Equation (2) defines the relation between gain, directivity, and efficiency of an antenna.

$$G = \eta \times D \quad (4)$$

where G = gain, η = efficiency, and D = directivity of an antenna.

Systematically, antenna array structure has been developed and presented in this paper where in initial phase, single and double DRA arrays have been configured. The said geometry is shown in Figure 1. The proposed CDRA structure is simulated using CST software.

2.1. Designing of Single Element and Double Elements Array

A single element structure consisting of one DRA, fed by a microstrip line, forms a simple geometry for analysis purpose. Here, the microstrip line is placed from the edge of the substrate to the center of DRA for adequate excitation. To achieve the desired response, appropriate Defected Ground Structures (DGS) length is optimised. The design geometry of single and double CDR antenna is as shown in Figure 1.

Here, a power divider (1 : 2) technique is utilised with equal spacing between the two elements for two elements DR antenna. The antenna element is combined with CDR microstrip and substrate. The CDR material is alumina ceramic having relative permittivity (ϵ_r) 9.8 and dielectric loss tangent ($\tan \delta$) 0.002. The diameter and height of CDR are 20 mm and 4 mm, respectively. FR4 is utilised as a substrate with relative permittivity (ϵ_r) 4.4 and dielectric loss tangent ($\tan \delta$) 0.004. The dimensions of substrate for a single element and double elements are (50 × 58 × 0.8) mm and (102 × 60 × 0.8) mm, respectively. All dimension details are shown in Table 1.

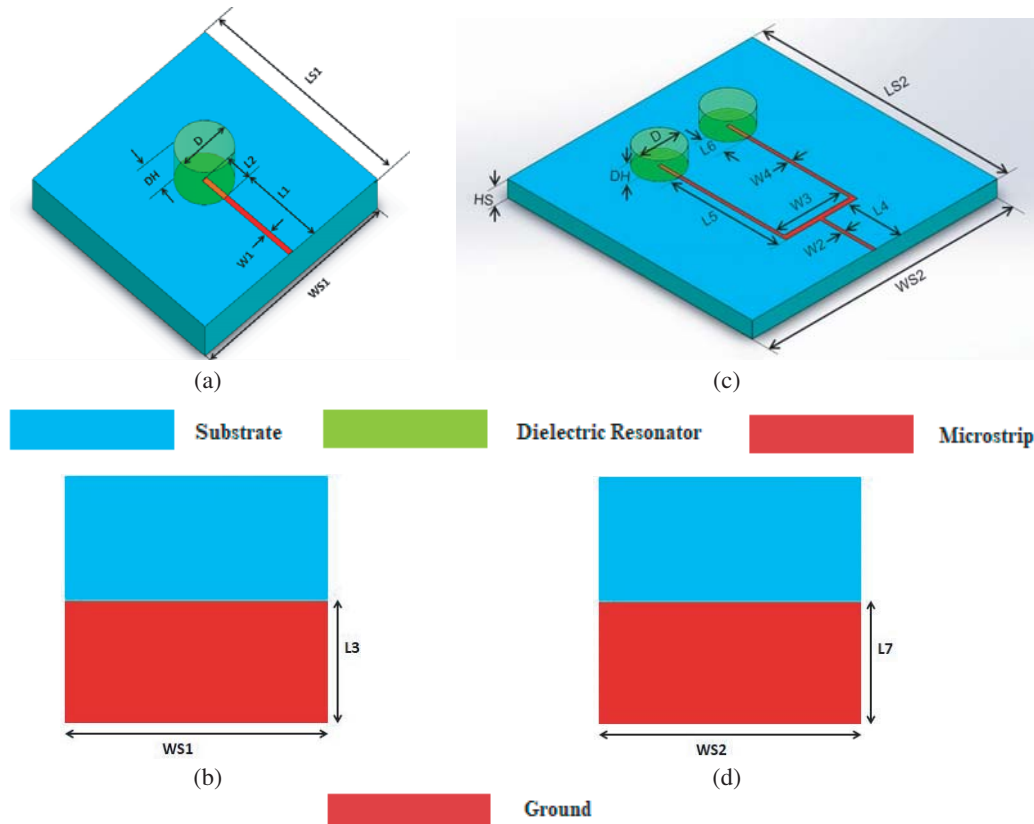


Figure 1. Single element (a) Ariel view (b) back view; Double element (c) ariel view (d) back view.

Table 1. Single and double element antenna dimensions.

Parameter	Dimension (mm)	Parameter	Dimension (mm)	Parameter	Dimension (mm)
<i>WS1</i>	58	<i>L4</i>	13.8	<i>L1</i>	18
<i>LS1</i>	50	<i>L5</i>	51	<i>L2</i>	9
<i>WS2</i>	60	<i>L6</i>	12	<i>L3</i>	15
<i>LS2</i>	102	<i>L7</i>	62.8	<i>W3</i>	22.8
<i>DH</i>	4	<i>W1</i>	2.4	<i>W4</i>	0.6
<i>HS</i>	0.8	<i>W2</i>	1.2	<i>D</i>	20

2.2. Designing of Developed Four Elements Array

The developed array structure is shown in Figure 2. Its Aerial view and back view are seen in Figures 2(a) and 2(b) respectively. The four CDRs, placed above the substrate, are identical and made from alumina ceramic material. Here, the power divider microstrip feeding structure is incorporated to achieve maximum impedance matching. The proposed CDRs are placed over an FR4 substrate with thickness of 0.8 mm. The distance between two pairs of CDRs and distance between each CDR and the aforesaid pair are carefully fixed to get the optimum response. As seen in Figure 2(b), dimensions of the ground plane and notch are carefully finalised using multiple iterations to get the acceptable return loss. All necessary dimension details are given in Table 2. Mutual coupling plays a vital role in antenna parameters such as impedance, bandwidth, and resonant frequency. The optimum distance between the two DRA elements (*D*) is kept as $\lambda/5$ for array design.

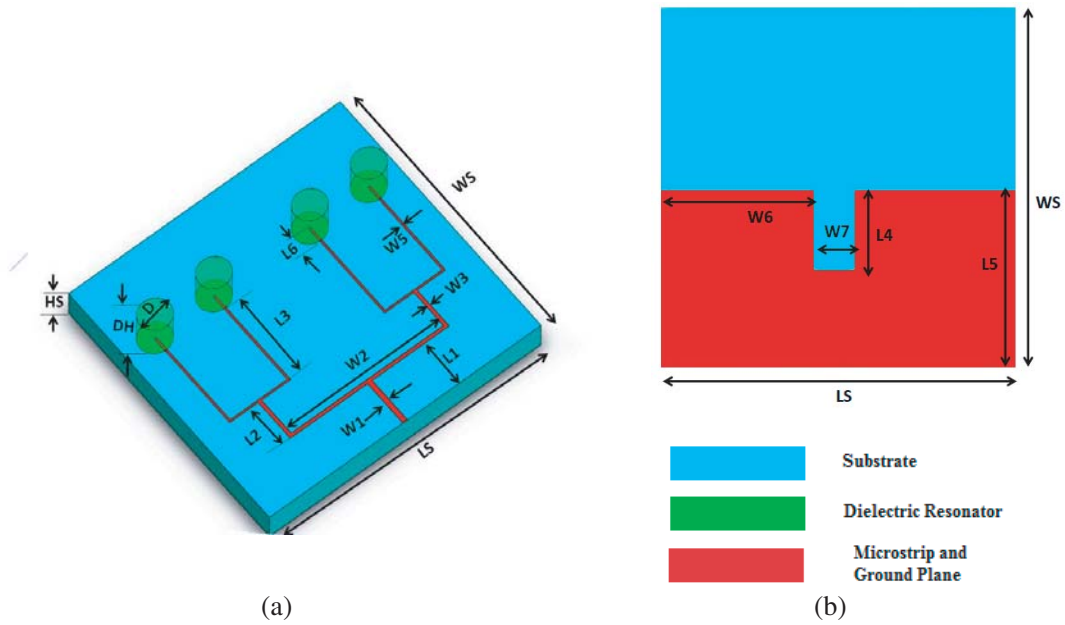


Figure 2. Proposed 1 × 4 element array antenna. (a) Aerial view, (b) back view.

Table 2. Proposed 1 × 4 element array antenna dimensions.

Parameter	Dimension (mm)	Parameter	Dimension (mm)	Parameter	Dimension (mm)
WS	120	$W1$	2.4	$L3$	63
LS	120	$W2$	57.6	$L4$	25
DH	4	$W3$	1.2	$L5$	80
HS	0.8	$W4$	22.8	$W7$	6
$L1$	16	$W5$	0.6	D	20
$L2$	15	$W6$	57	$L6$	20

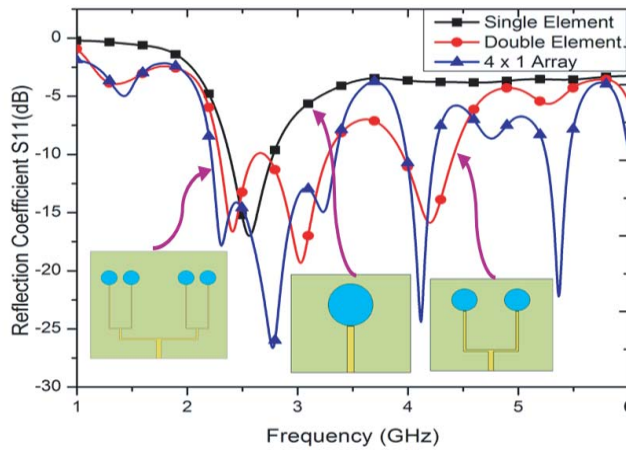


Figure 3. Simulation result of single, double and 1 × 4 element array antenna.

Figure 3 depicts comparison among simulation results of single, double, and 1×4 element CDRA's. It shows that a single element antenna can resonate in single frequency band; double element antenna can resonate in the double frequency band; and 1×4 element array can resonate at triple frequency bands. The gain of single element antenna is 1.94 dBi at 2.5 GHz frequency, and the gain of double element antenna is 4 dBi at 3 GHz frequency.

3. PARAMETRIC STUDY

The CDRA is excited by microstrip line feed to achieve required response. It has been observed that return loss varies with variation in the length of the feed line. In Figure 4(a), variation in responses (represented by colour lines) is shown for comparative study. It is clear that the triple bands with acceptable bandwidth (shown in black colour) could be achieved by 63 mm feed line length.

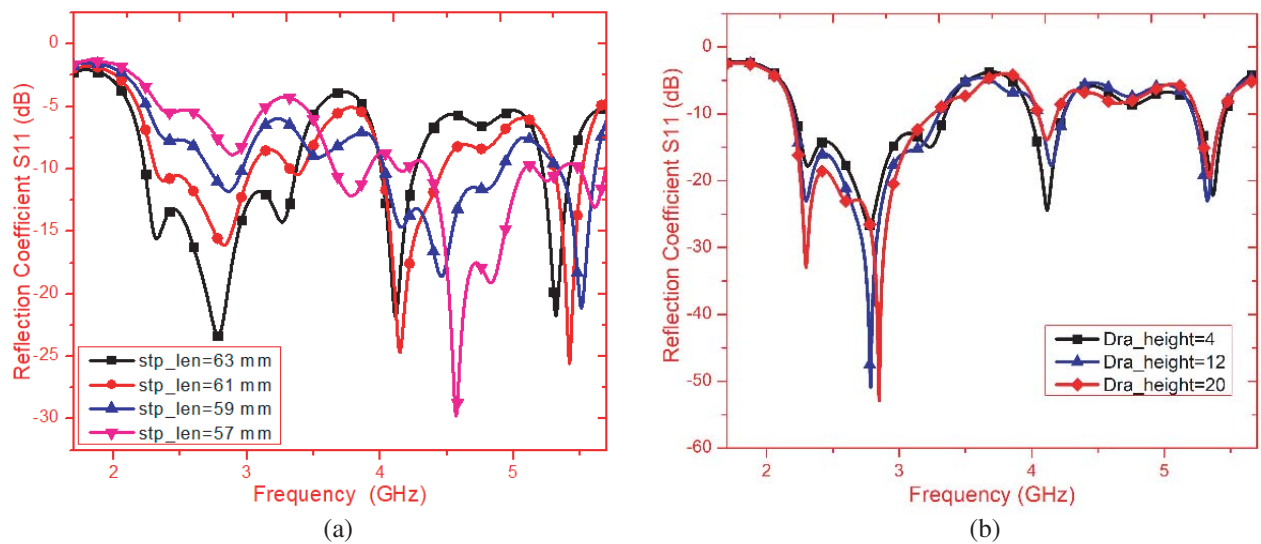


Figure 4. Simulation of parametric study: (a) variation in length of microstrip feed line (b) variation in DR height.

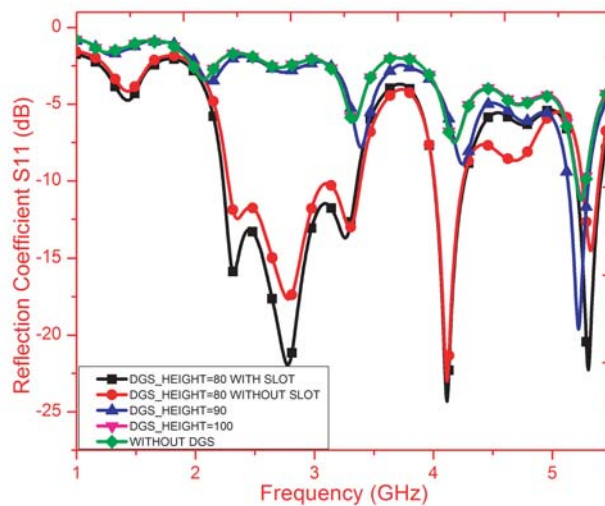


Figure 5. Simulation of parametric study of DGS length.

Similarly, the systematic analysis has been done by changing the height of the CDR to get the required response. Figure 4(b) gives its comparative study. The close observation suggests that the substrate with 4 mm height (shown in black colour) gives significant return loss with satisfactory bandwidth. So, the conclusion of the above discussion is 63 mm length feed line, and 4 mm substrate height has been finalised for fabrication of a similar prototype.

One more parametric study has been done where the height of ground plane has been varied to a certain level which is shown in Figure 5. The figure suggests that with 80 mm height (shown in black colour), higher bandwidth and triple-band response could be achieved, so it has been fixed along with aforesaid finalised parameters. As shown in Figure 5, introducing a slot in defected ground structure can achieve a good reflection coefficient (S_{11}).

4. RESULTS AND DISCUSSION

After the successful parametric study, various key parameters are finalized for the array design. The fabricated prototype of proposed structure is shown in Figure 6(a). Figure 6(b) shows a comparative study of measured and simulated results of 1×4 CDRA. Comparative study shows that there is close correlation between simulated and measured results. It can be observed from the figure that frequency is

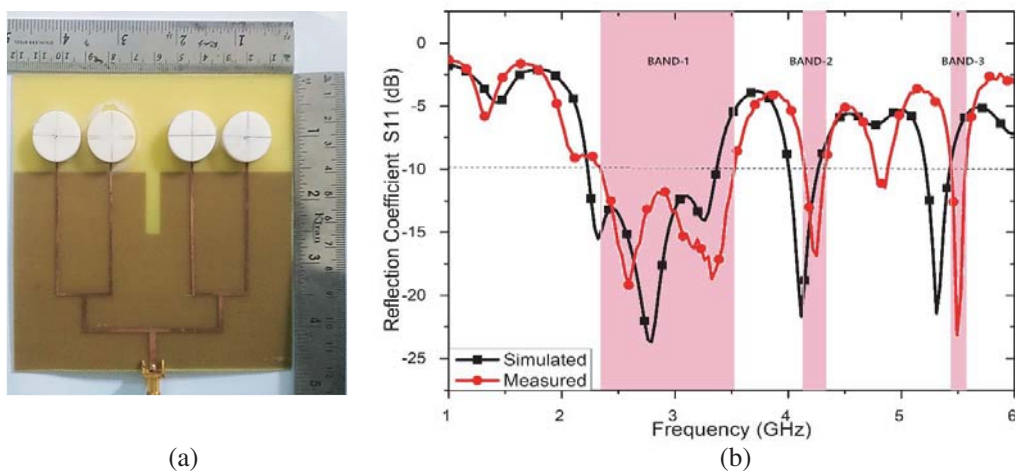


Figure 6. (a) proposed fabricated antenna (b) simulated and measured result of 1×4 CDRA.

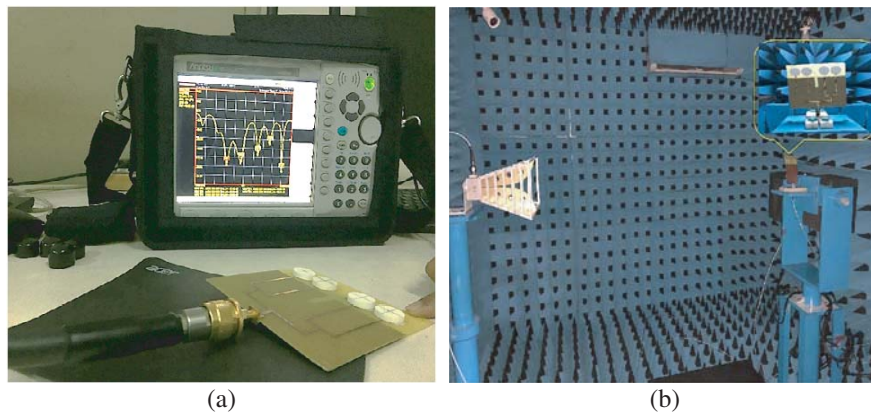


Figure 7. (a) fabricated antenna measurement with VNA (b) radiation patterns measurement of fabricated 1×4 CDRA.

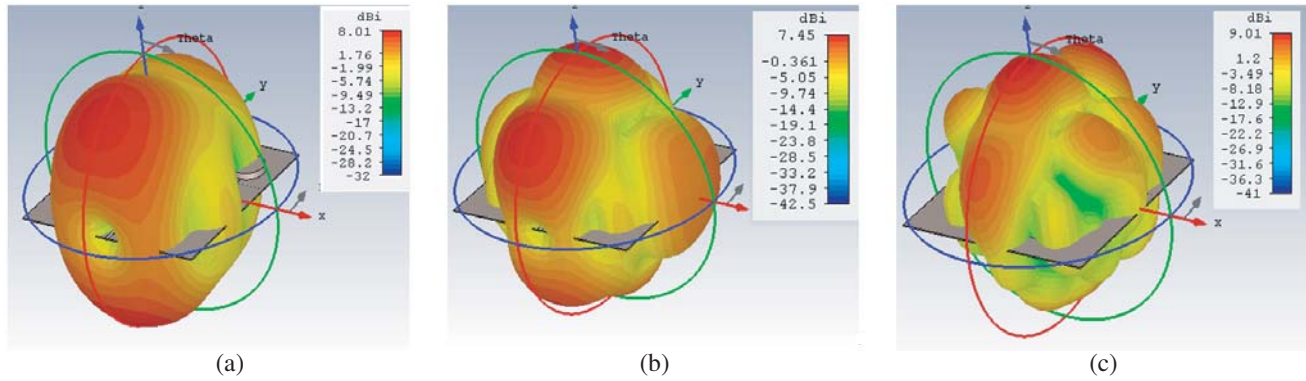


Figure 8. 3D radiation pattern for frequency (a) 2.4 GHz (b) 4.1 GHz (c) 5.4 GHz.

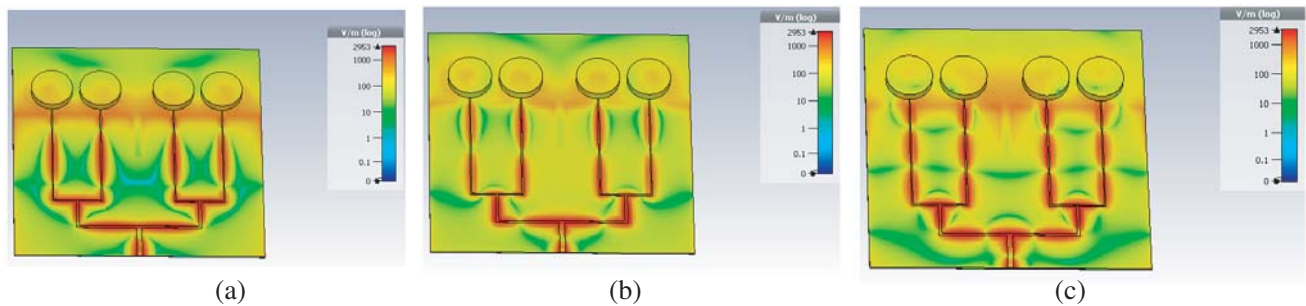
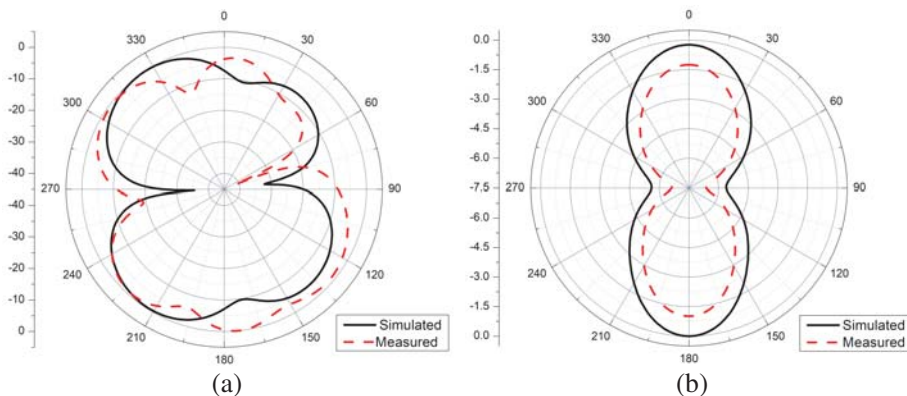


Figure 9. *E* field distribution throughout the array structure for frequency (a) 2.4 GHz (b) 4.1 GHz (c) 5.4 GHz.

shifted little to a side; however, required triple-band could be achieved which covers targeted frequencies of 2.4 GHz, 4.1 GHz, and 5.4 GHz with bandwidth of 1.14 GHz, 0.26 GHz, and 0.22 GHz, respectively.

As shown in Figure 7(a), the actual measurement is recorded using vector network analyzer Anritsu MS2037C. SMA connector is connected at the input side for power divider. DGS is properly implemented in the design to achieve maximum impedance matching and good return loss. Figure 7(b) shows the setup of an antenna test inside an anechoic chamber.

The 3D radiation pattern for different frequencies is shown in Figure 8. Here, the gains of 8.01 dBi, 7.4 dBi, and 9 dBi are achieved for frequencies 2.4 GHz, 4.1 GHz, and 5.4 GHz, respectively. As shown in the figure, most of the radiation is in the required direction. From the systematic analysis, it is found that good gain could be achieved by finding an optimum set of elemental amplitude excitation along with optimum inter spacing elemental. The phase excitation of 1×4 DRA array elements is kept at



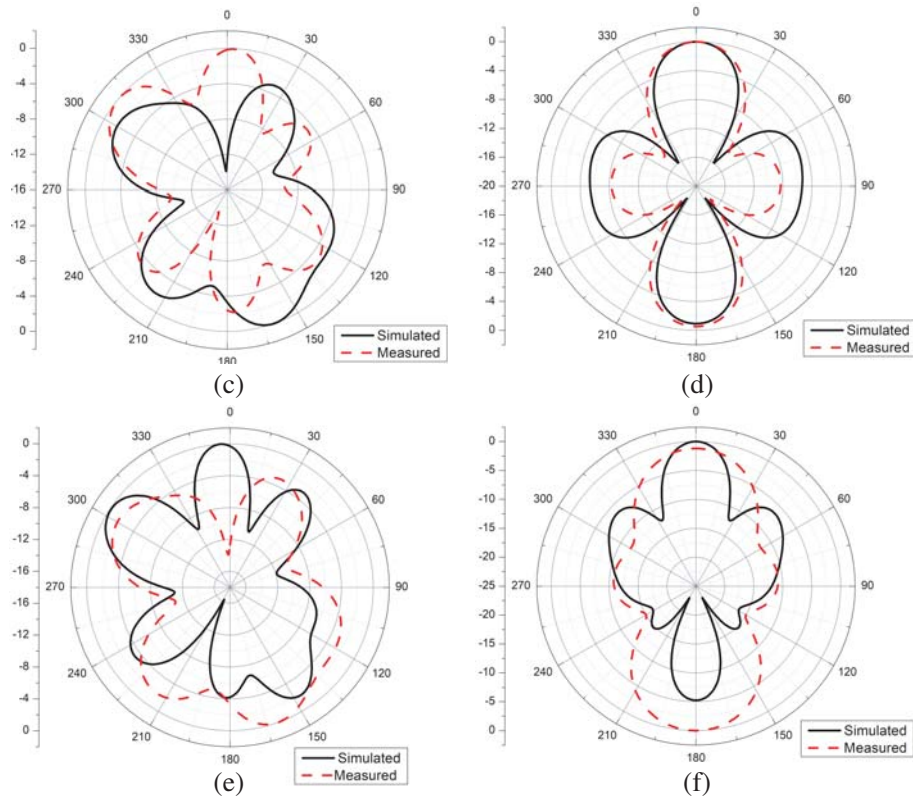


Figure 10. Simulated and measured radiation pattern of H field (a), (c), (e) and E Filed (b), (d), (f) for the frequencies of 2.4 GHz, 4.1 GHz and 5.4 GHz respectively.

Table 3. Comparison of the proposed DRA array with others antenna array.

Ref	Type of Feed	DRA Shape	DRA Material (ϵ_r)	Substrate (ϵ_r)	Total antenna size	Band-width (%)	Gain (dBi)	No. of Band
[10]	annular shaped microstrip feed	Cylindrical	Alumina Ceramic ($\epsilon_r = 9.8$)	FR4 ($\epsilon_r = 4.4$)	115 mm \times 80 mm	27	7.95	single (3.5–4.72 GHz)
[11]	aperture coupled	Cylindrical	Rogers 3010 ($\epsilon_r = 10.2$)	substrate Rogers 5870 ($\epsilon_r = 2.3$)	100 mm \times 85 mm	7	10	single (7.5–8 GHz)
[12]	Microstrip line	Rectangular	Eccostock HIK ($\epsilon_r = 20$)	Arlon AD270 ($\epsilon_r = 2.7$)	135 mm \times 48 mm	17	13.6	single (6.2–7.35 GHz)
[16]	Microstrip line	hemispherical	Eccostock HIK ($\epsilon_r = 20$)	Arlon AD270 ($\epsilon_r = 2.7$)	135 mm \times 48 mm	7.2	10	single (6.3–6.8 GHz)
Proposed antenna array	Microstrip line	Cylindrical	Alumina Ceramic ($\epsilon_r = 9.8$)	FR4 ($\epsilon_r = 4.4$)	120 mm \times 120 mm	40	9	Tri-band (2.23–3.37, 4.00–4.26 5.2–5.42 GHz)

zero degree that would reduce the complexity level of microstrip feed design. The proposed model gives 73.36% of radiation efficiency.

Figure 9 shows the E field distribution throughout the array structure for three different frequencies at 2.4 GHz, 4.1 GHz, and 5.4 GHz. Here, the maximum E field is found near the surface of the model for all desired frequency bands.

Figure 10 shows the E plane and H plane polar plots for 2.4 GHz, 4.1 GHz, and 5.4 GHz frequencies. The main lobe magnitude and 3 dB beamwidth are 8.01 dBi and 36.0° , 7.5 dBi and 37.1° , 9 dBi and 40.8° for the frequency 2.4 GHz, 4.1 GHz, and 5.4 GHz respectively.

Table 3 depicts the details comparison of DRA array designs in terms of shape, material, substrate, size, bandwidth, gain, and resonant bands. The comparison analysis shows that the proposed DRA array design gives rich performance especially in bandwidth, gain, and resonant frequencies.

5. CONCLUSION

A 1×4 DRA array structure with a microstrip feed line is successfully developed for applications of Wi-Fi, wireless LAN, and satellite communication. The demonstrated prototype gives adequate response at 2.4 GHz, 4.2 GHz, and 5.4 GHz frequencies. The presented array prototype is developed and fabricated using an FR4 substrate that gives cost effectiveness for bulk production. Here, the power divider technique is utilised for desired output. The presented antenna array design shows very close relation between simulated and measured results. By keeping an appropriate length of the microstrip line, height of the substrate and ground plane, the satisfactory response could be achieved.

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